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Methodology for Assessing the Environmental Impact of Wind Energy Facilities

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Abstract

The article presents a methodology for expert assessment of renewable energy facilities, in particular wind power plants (WPPs), on the environment. To assess the possible environmental impact of wind power facilities, an algorithm for solving this problem is proposed, based on the method of evaluating the ranks of expert judgments for the selection of experts and the method of analyzing hierarchies for determining the significance of the impact of WPPs on individual components of the environment. Experts assess the impact of environmental factors during the construction of wind power plants (WPPs) on the environment. The key environmental impacts of wind power facilities are analyzed and categorized into the following factors: air and water quality, geological conditions and soil integrity, biodiversity, public health, and the socio-economic dynamics of the region. The proposed methodology for expert assessment of the impact of wind power plants (WPPs) on environmental components has been practically tested. The results of the study show that in this region, the most significant environmental impact of wind farms is on the birdlife, 33.7%. A moderate negative impact is the impact on public health, 22.2%, on the geological environment of the territory and soil, 22.2%. A minor negative impact is the impact on air quality (10.0%), surface and groundwater quality (6.7%), and the socio-economic situation in the region (4.7%).

Keywords

Wind power plants; Environmental impact; Expert assessment; Priority vectors

Introduction

Currently, significant emphasis is placed on researching and developing the technical aspects of renewable energy utilization.

The International Renewable Energy Agency (IRENA), in its annual report, highlights key advancements and trends in the sector. Energy Statistics 2024 publishes statistics on various renewable energy technologies, indicating the volumes of installed capacity for the period 2014-2023 and the volumes of electricity production for the period 2014-2022.In the field of wind energy, both general statistics and specific data on onshore and offshore wind energy are provided. This international organization comprises 168 member countries along with the European Union. (Rahman, Farrok and Haque, 2022). Separately, wind energy is dealt with on a global scale by the Global Wind Energy Council (GWEC) and the World Wind Energy Association (WWEA). At the European level, the European Wind Energy Association (Wind Europe) coordinates wind energy activities. This organization publishes annual analytical reports on the development of wind energy in general (Wind Energy in Europe, 2023 Statistics and the Outlook for 2024-2030). In recent decades, we have been confronted with major climatic changes that affect not only humans but also flora and fauna, i.e., the entire economy. Electrification of the global economy in combination with rapid decarbonisation of the electricity grid is considered a key measure to mitigate climate change, i.e., to cut greenhouse gas emissions (GHG) and keep global warming to less than 2 °C (Vagiona, 2015). In this context, the electricity generation sector should make an important contribution by replacing power plants using conventional fuels with power plants using renewable energy sources.

Wind farms have attracted considerable attention as one of the most promising renewable energy sources. During their lifetime, wind turbines produce thirty to fifty times as much energy as they consume (Dammeier *et al*., 2019; Song, 2024], that is, the average energy payback of 5 to 10 months. Understanding the impact of wind farms on the environment is very important as wind farms, together with photovoltaic systems, are expected to produce over 60% of electricity by 2050 (Smolarz *et al*., 2023). Wind energy, often declared as a clean and renewable energy source, undoubtedly offers significant advantages over traditional fossil fuels, lowering carbon emissions and relying less on non-renewable energy sources, for example.

A survey by the National Renewable Energy Laboratory of large wind facilities in the United States found that they use between 30 and 141 acres per megawatt of power output capacity (a typical new utility-scale wind turbine is about 2 megawatts). However, less than 1 acre per megawatt is disturbed permanently and less than 3.5 acres per megawatt are disturbed temporarily during construction (Lopushanska *et al.*, 2024). The remainder of the land can be used for a variety of other productive purposes, including livestock grazing, agriculture, highways, and hiking trails (Smolarz *et al*., 2023). Alternatively, wind facilities can be sited on brownfields (abandoned or underused industrial land) or other commercial and industrial locations, which significantly reduces concerns about land use (Lopushanska *et al.*, 2024).

At the same time, the environmental safety of the impact of wind farms on the environment has not been sufficiently studied. When assessing the potential impacts of wind farms on natural complexes, it is important to take into account that these impacts may relate not only to wind turbines, but also to all related infrastructure: access roads, building structures, temporary contractor facilities, underground or overhead power lines, their supports, transformer substations, etc. And like all electric power generating

facilities, wind generators produce electric and magnetic fields. Although wind power plants have relatively little impact on the environment compared to fossil fuel power plants, concerns have been raised over the noise produced by the rotor blades, visual impacts, and deaths of birds and bats that fly into the rotors. By virtue of their aerial mobility, high public profile and the existing international and national legal frameworks relating to the specific protection of migratory species, birds feature prominently in the environmental impact assessment (EIA) process associated with wind farm developments, both on land and at sea. There is a burgeoning literature relating to the interactions between land-based wind turbines and birds. Direct mortality or lethal injury of birds can result not only from collisions with rotors, but also with towers, nacelles and associated structures such as guy cables, power lines and meteorological masts (Lezhniuk *et al*., 2022a). Environmental impacts can occur during any of the phases of wind farm construction, from construction (mechanical damage to vegetation, soils, geological structure, accidental or accidental pollution of water and soil by fuels and lubricants or transformer oils during construction) to operation (noise, blade flashing, electromagnetic radiation, vibration, visual impact due to changes in the landscape, fire risks, ice breaking off the blades), and the stages of restoration or decommissioning. Such impacts are particularly significant within the boundaries of nature reserves and international protected areas. In particular, the construction and operation of wind farms may result in the following impacts collision of birds and bats with various parts of the wind turbine or other structural elements of the wind farm, their injury and death, disturbance of animals and their relocation to other areas, barrier effect - wind farms with a large number of installations may lead to disruption of communication between feeding, resting and breeding areas, force birds or bats to change direction, in particular during migrations and flights on the ground, degradation and loss of habitat There might also be important interactions between habitat alteration and the risk of fatalities, such as bat foraging behavior near turbines (Lezhniuk *et al*., 2022b). The construction of wind farms on peatlands can lead to disturbance of water conditions, destabilization of peat, and an increase in carbon emissions, as peatlands as carbon storage are an important part of the climate change mitigation strategy. Other dynamic natural complexes, such as dunes and wetlands, are also vulnerable to changes that may be caused by the destruction of vegetation, disturbance of soil cover and geological structure, which can lead to erosion, destabilization, landslides, habitat degradation and loss (Kurbatova and Khlyap, 2015a).

The effectiveness of EIAs has been extensively discussed in the literature. Recent studies have shifted the focus from procedural effectiveness—centered on meeting regulatory requirements related to structure and methodology (Arts *et al*., 2012) — to substantive effectiveness, which prioritizes informed decision-making and considers the institutional design of EIA actors, their responsibilities, and the influence of their reports on policy processes. Despite certain, even fundamental, achievements, it can be argued that there are currently sufficient gaps in the implementation of environmental criteria for renewable energy sources in Ukraine. The key gaps, in order of importance, include the absence of: national strategies for the development of renewable energy sources in general and wind energy in particular as a key component of the sector; an approved methodology for developing environmental impact assessment reports for the construction of wind farms; expert commissions for environmental impact assessment as provided for by the Law on Environmental Impact Assessment. This research gap prompts critical questions as to whether formal understanding of the EIA alone is

sufficient to understand the decision-making process (Ivanov, Lopushanska and Teslovych, 2022). The implementation of new facilities, including wind power plants (WPPs), requires a complex of pre-investment studies, which should consist of an assessment of the wind energy potential of the territory, geospatial planning taking into account restrictions, and an environmental impact assessment procedure. The urgency of the problem lies in the rapid construction of wind energy facilities without scientific substantiation of their environmental safety, which may cause the suspension of investment projects due to refusal or issuance of a negative conclusion on the environmental impact assessment due to the presence of significant impacts, public opposition, and inconsistency with target programs for the development of territories (Kurbatova, Sotnyk and Khlyap, 2014). Therefore, studies aimed at improving individual stages of the environmental impact assessment procedure for wind energy projects are relevant and important for increasing the level of environmental safety when using wind energy (Kurbatov and Khlyap, 2015b). The article investigates the advantages and usefulness of the development of renewable energy sources, which are considered along with analysis of the most economically profitable directions of their use. The key obstacles, which reduce the effectiveness of RE deployment and barriers to the realization of RE projects by investors are analyzed.

Literature Review

Environmental impact assessment (EIA) is a complex issue as it seeks to determine the basic components responsible for the overall environmental burden of the project/activity so as to plan suitable measures to mitigate these impacts. The evaluation of impact significance is considered as one of the most difficult, critical and vital element of the process. There are many tools and techniques that have facilitated the impact assessment processes such as scoping, checklists, matrices, qualitative and quantitative models, literature reviews and decision support systems (Munier, 2004). There is also a vast multi-criteria decision-making literature, which deals with EIA problems and the application of multi-criteria assessment (MCA) methods to support complex environmental decision making has gained great interest in the last decades (Janssen, 2001). The problem of environmental impact assessment was addressed by (Kaldellis *et al.* 2016). The article analyzes the current development of wind energy in the world, its growth trend and adverse environmental consequences. In particular, the authors provide an approximate list of impacts that the construction of an onshore wind farm may cause: noise effects, landscape changes, deforestation and soil erosion. In addition, possible ways to address the above-mentioned adverse environmental impacts on wind energy production facilities are presented (Nazir *et al.*, 2020). A number of publications analyze the problems of developing various types of renewable energy and their effect on the environment. In the publication (Nazir *et al.*, 2020) on the global development of wind energy. Comparative characteristics of wind and solar energy are given in the works (Ahamed and Alshare, 2022; Song, 2024). The document (Rahman, Farrok and Haque, 2022) presents a comparative SWOT analysis for solar photovoltaic and concentrated solar power plants. In a comprehensive comparison of wind and solar energy, three key aspects are focused on cost, efficiency and environmental impact. The comparisons include the initial and ongoing costs associated with the creation and maintenance of each energy system, the efficiency of converting natural resources into affordable electricity and the environmental impact, including potential disruption of local

ecosystems and land use. The identification and assessment of the environmental impact of wind farm projects in the Central Greece region, as well as possible solutions to the above-mentioned problems, are highlighted in the work of Greek researchers. For this, a modified Rapid Impact Assessment Matrix (RIAM) method is used. The methodology involves identifying existing onshore wind farms projects within the study area, adapting the RIAM method to align with the specific characteristics of the projects and regional conditions, qualitatively assessing their potential impact during the construction and operational phases, and calculating the Environmental Performance Grade (EPG) using the modified RIAM approach (Korozi and Vagiona, 2024).The authors of the article (Pastakia and Jensen, 1998) present a consolidated impact assessment matrix, attempting to transparently incorporate subjective judgments into the environmental impact assessment process. The study by Ahamed and Alshare (2022) summarizes the environmental impacts of solar and wind energy systems in terms of the following factors: land use, water consumption, impacts on biodiversity, visual and noise effects, health problems, and impacts on microclimate. However, there is still no algorithm for assessing the environmental impact of wind energy based on mathematical modeling of processes.

Methodology

The authors proposed a combined methodology for expert assessment of the impact of renewable energy facilities, in particular wind power plants, on the environment, using the method of consistency of expert judgments regarding the assessment of impact criteria and the method of hierarchy analysis (Saaty, 1992). The peculiarity of this method is the absence of clearly formalized evidence of the influence of a particular factor on the final result of decision-making. Due to the impossibility of obtaining clear, complete and reliable information, the value of a particular factor is not the value itself, but the judgement of an individual about its value expressed by an individual. When applying this method, groups of experts are formed from leading specialists who deal with the environmental impact of wind farms, identify the main factors that influence decision-making, and draw up a questionnaire and a scale of evaluation criteria.

In cases where reliable information about the impact of various factors on wind energy is lacking, the method of expert assessments is employed. A feature of this method is the lack of clearly formalized evidence of the impact of a particular factor on the final result of decision-making. Due to the impossibility of obtaining clear, complete and reliable information, the value of an individual factor is not the value itself, but the judgment about its value expressed by a person (expert).When applying this method, expert groups are formed from leading specialists, the main factors for decision-making are established, a questionnaire and a scale of assessment criteria are compiled. An important aspect of the expert assessment method is determining the significance of both individual factors and expert judgments. Thus, solving this problem involves the following steps: selecting competent experts based on their ranks, identifying the dominant environmental impact factors and compiling a database of input information, processing the input data to determine the significance of factors, and formulating conclusions and recommendations. The algorithm for solving this problem is presented below.

Consistency of Expert Judgments Regarding Assessment of Impact Criteria

In order to establish the significance of individual factors and experts' judgments, the method of rank correlation is most often used. The implementation of this method includes the following stages: at the first stage, a system of factor ranks is determined and their significance is established; secondly, the evaluation of expert ranks and judgment consistency – assessing the ranks of experts and measuring the level of agreement among their judgments. The key criterion for determining the consistency of experts' judgments is the concordance coefficient (Grabovetskyi, 2000):

$$W = \frac{12\sum_{j=1}^{n} d_j^2}{m^2(n^3 - n) - m\sum_{i=1}^{m} T_i}, \quad (1)$$

where m is – number of experts; n is – number of factors.
The value d_j represents the deviation of the sum of the ranks of a single factor j from the average value of all factors. That is

$$d_j = S_j - \frac{\sum_{j=1}^{n} S_j}{n}, \quad (2)$$

where S_j– rank of the factor j and

$$\sum_{i=1}^{m} T_i = \sum_{i=1}^{e} (t_e^3 - t_e) \quad (3)$$

where e– number of groups of related (identical) factors; t_e – number of related ranks of each group. In the absence of related factors, formula (3) takes the form.

$$W = \frac{12\sum_{j=1}^{n} d_j^2}{m^2(n^3 - n)}. \quad (4)$$

The concordance coefficient value determines the level of agreement among experts as follows: (0–0.2) – inconsistent; (0.2–0.4) – weakly consistent; (0.4–0.6) – noticeable consistency; (0.6–0.8) – good consistency; (0.8–0.9) – strong consistency; (0.9–1.0) – very high consistency. Solving the problem at this stage allows the preliminary selection of competent experts according to their ranks. Only after determining the ranks of experts and preliminarily establishing the level of consistency of expert judgments can one proceed to the next stage - determining the relative importance of the criteria, as well as their weight, using the method of analysis of hierarchies (AHI).Solving the task at this stage allows us to pre-select competent experts according to their ranks.

Criteria for Selecting Respondents

1. Availability of a qualification certificate in valuation. 2. Degree of expert competence. Its indicators are academic degree, title, work experience in the specialty, official position, number of publications on the issue, activity in a particular area, involvement in the problem, etc. 3. The expert should be aware of the latest achievements of modern science in the areas of expertise. 4. The ratio of narrow specialization and the general

outlook of the expert. 5. The expert's ability to analyze and synthesize the problems under study, the ability to process and assimilate qualitatively new information. 6. High moral qualities of the expert.

Hierarchy Analysis Method

Evaluation Metrics

The main feature of this method is to determine the weight of each evaluation criterion and, thus, determine their relative importance in the final decision made within the model. The method is based on pairs of factor comparisons (Fi) within the inverse matrix. Accordingly, a comparison matrix is created between pairs of criteria, contrasting the importance of each pair with all others. A priority vector is calculated for establishing weights (ωj). These weights are a quantitative indicator of the consistency of evaluation judgments between pairs of criteria.

Algorithm Implementation

The use of AHI involves the implementation of the following stages: forming a matrix of pairwise comparisons and calculating evaluation coefficients for the elements of each factor; checking the consistency of judgments; determining the values of quality indicators for each factor. The computational basis of the AHI is the matrix of pairwise comparisons of factors (Table 2), where the scale of expert point evaluation values (Table 1) is used to form the matrices of pairwise comparisons.

Table 1: Saaty's nine-point scale of evaluation

Assessment of the importance of the criterion	*Description of the importance of the criterion*	*Level of suitability*
1	Equivalent	The lowest suitability
2	Equivalent to moderate	Very low suitability
3	Moderate	Poor suitability
4	Moderate to large	Moderately low suitability
5	Great	Moderate suitability
6	Large to very large	Moderately high suitability
7	Very large	High suitability
8	Very large to extremely large	Very high suitability
9	Extremely large	Highest suitability

Table 2: Fragment of the pairwise comparison matrix

	F1	*F2*	*F3*
F1	1	F1F2	F1F3
F2	F2F1	1	F2F3
F3	F3F1	F3F2	1
Σ			

As a result of mathematical transformations, we create a normalized matrix, where we determine the priority vectors (ωj), which are the result of dividing each judgment value (Fi) by the sum of the values of the corresponding column 9 (Table 3).

Table 3: Normalized pairwise comparison matrix

	F1	*F2*	*F3*	*Priority vector (average value for each criterion - Weight)*
F1	1/ΣF1	F1F2/ΣF2	F1F3/ΣF3	ω1
F2	F2F1/ΣF1	1/ΣF2	F2F3/ΣF3	ω2
F3	F3F1/ΣF1	F3F2/ΣF2	1/ΣF3	ω3
Σ				1

The calculation of the priority vector by the pairwise comparison matrix is the calculation of the main eigenvector, which, after normalization, becomes the priority vector. Estimates of the value of the main eigenvector can be obtained in the following four ways: sums by rows; sums by columns; reciprocals; geometric mean values by row.

To assess the consistency of the criteria, the Consistency Index is calculated.

$CI = \frac{(\lambda - n)}{(n-1)}$, where (5)

CI - consistency index; λ - average value of consistency vector; n - number of criteria. The reliability of the consistency index is determined by comparing it with the Random Index (RI),

$$CR = \frac{CI}{RI}, \qquad (6)$$

where CR is the value of the correlation coefficient; CI is the correlation index; RI is the random index (Random Index), obtained by approximating the random indices (Saaty, 1992). If CR<0.10, the coefficient indicates a good level of agreement in pairwise comparisons; if CR>0.10, the coefficient values indicate contradictory judgments. In such cases, the initial values in the pairwise comparison matrix should be revised.

Results

The territory of Ukraine was selected for the implementation of this methodology. The design of wind turbines requires the solution of several complex technical and economic problems: selection of the construction site (geographical location); analysis of the ecological component of the selected site; determination of the technical feasibility of using the proposed site for the construction of wind turbines; estimated wind flow power in the wind farms construction area; determination of the main economic indicators of the future WPP. The sites for the installation of wind power plants (WPP) were chosen from reserve lands that are not used for economic or industrial purposes. The distance from the projected (WPP) to the nearest residential building is more than 700 m (Figure 1).

The territory of the wind farms consists of two separate plots. The approximate size of the land for the construction of one wind farmis 1 ha. Depending on the model, the height of the tower is 105 - 166 m. The assessment of the significance of the impacts on the environment was carried out on the basis of the analysis of data from the pre-project documentation, scientific research, EIA reports of similar projects, cartographic information and field observations. An expert assessment method was used to establish the impact of environmental factors on the environment. In the process of carrying out this work, a survey and questionnaire were conducted with 12 qualified experts who deal with land management, cadastre, ecology, etc. According to the results of the assessment

of expert judgments, 10 experts were selected whose consistency results were good and high (W = 0.8 - 1.0). Experts identified, in their opinion, six of the most important components of the environment that could potentially be most affected by the construction, operation and liquidation of wind farms. These components are recognized as key environmental factors and include: flora and fauna; geological environment and soils; health of the population of the surrounding area; air quality; quality of surface and groundwater; and socio-economic situation of the surrounding region. By comparing the impact of wind farms on these components in pairs, assessments were established and a corresponding matrix was formed (Table 6). The assessments were made in points, and for a comprehensive assessment, the task was set to generalize the results and determine the coefficients of the relative importance of each factor.

Figure 1: Wind farms location scheme

Flora, Fauna and Biodiversity

Wind farms also have an impact on flora and fauna. A comprehensive description of these impacts was given by Sai, Khavar and Vinarchyk (2020). According to them, the main impacts of wind farms on the local ecosystem include the risk of mortality due to collisions of birds and bats with the wind turbine, migration due to disturbance (including noise), barrier effects, loss of habitat and indirect impacts at the ecosystem level. The assessment of significance is based on taking into account the sensitivity of components and receptors, which is especially characteristic of flora, fauna and biodiversity. High sensitivity is inherent in protected areas and species. Given the distance to sensitive areas, flora will be affected mainly during the preparation of the construction site through soil removal. The construction of the wind farms and infrastructure does not involve deforestation. Table 4 shows the list of the Nature Reserve Fund (NRF) objects closest to the study area, as well as their proximity to the area of the wind farms. The significance analysis is based on the sensitivity of the components and receptors, which is particularly relevant for flora, fauna and biodiversity. The areas and species under protection are characterized by high sensitivity. The closest protected areas of local importance are the Cholga Bird Sanctuary. Given

the distance to the sensitive areas (2 km), the impact on flora will mainly occur during the preparation of the construction site due to excavation.

Table 4: Nature Reserve Fund (NRF) objects closest to the study area

Name of the territory or object of the nature reserve fund	*Category*	*Type (object of protection)*	*Location of the territory or object of the nature reserve fund*	*Minimum distance to the wind farms*
Territories and objects of the nature reserve fund of national importance				
Yavorovsky	National natural park			15 km
Territories and objects of the nature reserve fund of local importance				
Boring	A natural reserve			12 km
Cholginsky		ornithological	Cholhyni village	2 km
Lubinsky	nature reserve	forest	MalyiLubin village	10 km
Solonitsa	урочище	tract	State Enterprise Sambir Forestry	20 km

Additionally, research into wildlife behavior and advances in wind turbine technology have helped to reduce bird and bat deaths. For example, wildlife biologists have found that bats are most active when wind speeds are low. Using this information, the Bats and Wind Energy Cooperative concluded that keeping wind turbines motionless during times of low wind speeds could reduce bat deaths by more than half without significantly affecting power production (Kamp *et al.*, 2016). Other wildlife impacts can be mitigated through better siting of wind turbines. The U.S. Fish and Wildlife Services has played a leadership role in this effort by convening an advisory group including representatives from industry, state and tribal governments, and nonprofit organizations that made comprehensive recommendations on appropriate wind farm siting and best management practices (Kamp *et al.*, 2016).

A grey heron nests near the wind farms on the territory of the Cholginsky bird sanctuary. Displacement of protected birds from their habitats. Given that during the nesting period, wind farms do not significantly affect birds, except for ducks, geese, and some other species of waterfowl and open-space birds that avoid wind farms. Some species, in particular the gray heron (whose nesting is protected nearby), birds of prey, starlings, and crows, can often be found near and even within the boundaries of wind farms, which can partially lead to an increase in the likelihood of death in a collision with wind farms. Wind farms located near water bodies or bare mountain ranges cause more casualties than others. Loss of resting and feeding areas for migratory birds. Wind farms have a very large effect on migratory birds outside the breeding season, displacing them from resting and feeding areas. Literature data, in particular (Wang, Wang and Smith, 2015), in which the author analyzed 180 papers on the impacts of wind turbines on birds and

bats, indicate certain species-specific behavioural characteristics. For some species, a significant relationship between the height of the wind farms and the avoidance distance is evident (Nazir *et al.*, 2020). Some species, such as grey herons, birds of prey, starlings, and crows, have been frequently observed near and even within wind farms, which has partly contributed to the increased likelihood of collision and mortality. Wind farms located close to water bodies or bare mountain ranges cause more casualties than others. Bird collision rates also correlate with turbine height. On average, a wind turbine with a height of 100 m accounts for 5 bird fatalities per year. The southern continental Eurasian flyway passes through Ukraine, and the study area is the northwestern spring migration flyway and the Carpathian autumn migration flyway. The construction of wind farms may cause the displacement of bats from their ranges due to the loss of feeding areas or disruption of movement corridors. High collision rates for bats are characterized by wind farms located near forests. Additionally, research into wildlife behavior and advances in wind turbine technology have helped to reduce bird and bat deaths. For example, wildlife biologists have found that bats are most active when wind speeds are low. Using this information, the Bats and Wind Energy Cooperative concluded that keeping wind turbines motionless during times of low wind speeds could reduce bat deaths by more than half without significantly affecting power production (Zielinski, Bela and Marchlewski, 2010). In particular, sparrow-like birds flew mainly at altitudes up to 40 m, ducks and cranes - at altitudes above 120 m, and raptors - equally often at different altitudes. The construction of wind farms can lead to the displacement of bats from their habitats due to the loss of foraging areas or disruption of movement corridors. Wind farms located near forests have high collision rates for bats. Collision rates in these sensitive areas were many times higher, with some wind turbines killing more than 100 bats per year (Wang, Wang and Smith, 2015). Since bats are one of the most vulnerable groups of mammals, most species living in Ukraine are listed in the Red Book. In particular, in the USA, up to 400,000 birds die each year due to collisions with wind turbines (Torres and Petrakopoulou, 2022). Analyzing international experience, we can conclude that wind farms will affect avifauna due to the relative proximity of their location to forest and water bodies, therefore, constant monitoring studies are necessary during construction and operation for changes in bird and bat populations, recording facts of death from wind farms and, if necessary, changes in the operation of wind farms to reduce risks during migration. Among the components of the natural environment, avifauna may be moderately negatively affected due to the death of protected birds and bats in a collision with wind farms, the displacement of species from their ranges, and the effect on migratory birds. Monitoring studies of changes in populations during construction and operation, recording facts of deaths from wind turbines and, if necessary, stopping wind turbines, applying measures to prevent and scare birds to reduce risks during the migration period will make it possible to mitigate these impacts.

Geological Environment and Soils

The construction of wind farms involves considerable intervention in the soil, including the clearing of vegetation, excavation work and the construction of access roads. These activities can lead to soil compaction, erosion and loss of soil structure. Soil compaction can reduce the soil's ability to absorb water, leading to increased runoff and erosion. This can also lead to sediment and pollutants entering nearby water bodies and degrading water quality. Wind farms can also lead to a significant reduction in soil moisture, which

can further exacerbate soil degradation and affect local vegetation (Li *et al*., 2024; Lopushanska *et al*., 2024).

According to the structural and tectonic zoning, the wind farms location site is within the Precarpathian depression. The maximum absolute height of the site is 306.00 m. In engineering and geological terms, the territory is characterized by the following indicators by the slope of the land surface from 0.5 to 20%, and by the depth of groundwater from the land surface, 1.8-2.0 m. The relief of the site is calm, with a decrease in the southern direction. The main effect on soils occurs during the preparation of the wind farm's construction site and consists of the excavation of soil during the construction of underground parts of buildings, road surfaces, underground networks, drainage structures, as well as fertile soil for landscaping the territory. The negative impact will be reduced by the re-cultivation of the surface soil layer and the restoration of vegetation, using technological passages. The removal of land for wind farms may result in habitat loss and impacts on terrestrial ecosystems. This impact will be mitigated by re-cultivation of the surface soil layer and restoration of vegetation cover, avoidance of construction on the territory of the nature reserve fund, and locating the wind farms in a non-forested area.

Public Health

It should also be emphasized that the use of wind turbines instead of power plants using conventional fuels contributes to a significant reduction in the emission of PM 2.5 particles, which are a major problem for human health, and the emission of other harmful substances. As a result, the non-carcinogenic toxicity potential for humans over the entire life cycle is one of the lowest for wind turbines (Pastakia and Jensen, 1998).

When assessing this component, data from domestic and foreign studies, the practice of similar projects, and experimental studies were analyzed. According to (Cunney *et al.*, 2014), who conducted a critical review of 162 scientific papers, there is no evidence that wind turbine noise is associated with any clearly defined disease outcome. However, varying proportions of people living near wind farms complain about wind farms or their noise (Rahman, Farrok and Haque, 2022).During construction work and at the stage of liquidation of the object, impacts related to noise, air pollution, and vibrations will occur. Wind turbines are being built on agricultural lands far from the nearest houses. There will also be a threat to people's lives due to construction work and the movement of vehicles on public roads. The elimination of such threats will be ensured by proper organization of work, marking of work areas, establishing optimal routes for transporting materials, and, if possible, limiting the movement and operation of equipment during the day. Due to the operation of the object, there will be no serious negative effect on the living conditions and health of people. Environmental quality standards will be met. According to (DBN V.1.1-31:2013) protection of territories, buildings and structures from noise for territories directly adjacent to residential buildings, the permissible equivalent sound pressure level is 55 dBA during the day, 45 dBA at night, the maximum permissible sound pressure level is 70 dBA, 60 dBA, respectively. The impact of noise, electromagnetic fields, and radiation will not exceed permissible standards. The effect of shadow flicker and ice scattering by blades will occur only during the operation phase of the facility. In Ukraine, there are no regulations on shadow flicker. International

guidelines for planning wind farms (Israel, Ivanova and Ivanova, 2023**)** are guided by the following provisions: maintaining sufficient distance; the effect of shadow flicker on buildings in the area of influence within a certain regulatory time; application of mitigation measures, such as turning off turbines at certain times, planting trees in the area between wind farms and buildings. According to theoretical calculations, for wind turbine generators with an axis height of about 117 m, the ice scattering distance is about 364.5 m. The threshold value for the impact of shadow flicker on each dwelling is 30 hours per year and 30 minutes per day. For two dwellings, these requirements are slightly exceeded, however, wind turbines that create such an effect will be equipped with a system that will limit their operation in such a way that the threshold values are not exceeded. Noise during construction will be noticeable, in particular from transport and construction equipment. To reduce the effect on workers, hearing protection is provided during construction, and construction work will also be carried out during the day. Noise pollution occurs during the operation of the power plant's electrical equipment. Implementing noise-reducing equipment can help minimize this environmental impact. To predict sound pressure levels (sound level) at a certain distance from windfarms, the laboratory of 'Company "Center LTD" LLC conducted a study of the average value of sound pressure levels in octave frequency bands and equivalent sound levels. The sound level was measured with an Ecophysics - 110A sound level meter (Table 5). Protection of territories, buildings and structures from noise for territories directly adjacent to residential buildings, the permissible equivalent sound pressure level is 55 dBA during the day, 45 dBA at night, the maximum permissible sound pressure level is 70 dBA, 60 dBA, respectively(DBN A.3.1-5:2016). The above facts allow us to state that the noise levels generated by the projected wind farm will not exceed the standards established at the border with residential development, and the minimum distance from residential development to the wind farm is more than 700 m (Table 5).

Table 5: Noise level measurements

№	Measurement point	Time of day	Sound levels
1	Measurement point-1 at a distance of 200 m	Daytime hours	44.3 dBA, with a permissible level of 55
2	Measurement point - 2 at a distance of 450 m	Daytime hours	39.1 dBA, with a permissible level of 55

Electromagnetic radiation. Recently, the close attention of the modern scientific and medical organizations has been drawn to electromagnetic radiation harm on human health and the environment. The increasing number of industrial and electric equipments with high frequency is the main reason of electromagnetic pollution. The harmful effects of industrial and high frequency EMFs on human health are confirmed by many studies (Milham and Morgan, 2008).

Monitoring of the environmental electromagnetic pollution is one of the most important tasks for any country to ensure public health and safety. According to various information sources research on the EMFs near the windmills shows opposite results. As an example, the Australian researchers' team (Israel, Ivanova and Ivanova, 2011). has found that electromagnetic radiation near the wind turbine is much lower than the normalized values, and therefore there is no harmful impact on environment, as well as on a human health. However, the independent researchers from Ontario (Canada)

have found that electromagnetic waves generated by the turbines contain a significant amount of high-frequency components which cause the weakness and diseases among the local residents (Israel, Ivanova and Ivanova, 2011).

Wind farms (wind turbines, transformer substations and cable lines) are sources of electromagnetic radiation, which are characterized by electric field strength E (V/m) and magnetic field strength H (A/m). The impact of electromagnetic fields on the population in each country is regulated by relevant state acts. In this case, the wind farms are located outside the residential area.

Air Quality

Wind power provides climate, air quality, and health benefits by displacing the emissions of both greenhouse gases and air pollutants such as SO_2 and NO_x from fossil fuel electricity generating units (EGUs). Compared with longer-term and globally distributed climate benefits, the immediate and local air quality benefits of wind power development have the potential to incentivize policy-makers to take measures to address global energy and climate challenges. In the United States, much wind power development has historically been driven by the state-level renewable energy policies [such as a renewable portfolio standard (RPS)] (Carley *et al*., 2018; Hubar *et al.*, 2023).

Some negative impacts of the project may be felt during the construction of the wind farms, in particular during the construction of the road network and auxiliary structures. These impacts include air pollution from construction equipment and transportation, as well as dust formation. Short-term local air pollution from exhaust gases and dust generated by vehicles and construction machinery will be observed, especially during the construction and decommissioning stages. This is comparable to any other construction work, and a serious polluting effect on the air is not expected. The operation of wind farms will not cause air pollution. On the contrary, the production of energy from renewable sources, namely from wind, will prevent the emissions of pollutants that would be generated by a power plant of the same capacity using traditional fuels. This positive impact will persist throughout the entire service life of the wind farms.

Surface and Groundwater Quality

When wind farms are built in karst areas, the major interest for researchers, communities and economies is to evaluate the impacts on the quantity and the quality of groundwater. This is because karst areas are of fundamental importance to people since they hold huge groundwater reservoirs, which feed springs and represent the main source of fresh water in many areas of the world (Gunn, 1998). The recharge of the groundwater resources is produced by the infiltration of the surface water into the underground, which occurs in a concentrated or diffuse manner (Smolarz *et al.*, 2023). Concentrated infiltration occurs at points, such as sinkholes/shafts and swallow holes, and allows for the fast transfer of water from the surface to the underground. On the other hand, diffuse infiltration occurs via the soil mantle or fractures in the outcropping karstrocks, and generates percolation, which can take a significant amount of time before water reaches the water table (Fiorillo, Pagnozzi and Ventafridda, 2014).

During construction and decommissioning, surface and groundwater may be at risk due to improper storage of construction materials and breakdown of equipment and vehicles, which may cause leakage of operating fluids. During operation, the effect on surface water may be caused by the following: uncontrolled oil spills during maintenance of wind turbine generators; uncontrolled oil spills, fuel and other technical fluids from machinery and specialized equipment used for maintenance and repair of wind turbine generators; accidental spillage of transformer oil into the central substation. Due to the nature of the operation of the wind farms, which does not require maintenance, the designed investment facility will not be a source of domestic or industrial wastewater. Water pollution: The construction phase may impact surface water quality, leading to changes in surface runoff volume due to soil disturbance and the removal of vegetation. The effect on groundwater pollution is possible in the form of increased water inflow into groundwater due to soil degradation and the inflow of pollutants into groundwater.

Socio-Economic Situation

Many challenges facing wind power expansion relate to local resistance (Scherhaufer *et al*., 2017) because of concerns about changes to scenic landscapes and adverse effects on biodiversity,11 ecosystems, human health, or local economic impacts (Gkeka-Serpetsidaki and Tsoutsos, 2023). Other challenges stem from restrictive or inefficient regulation, which results in excessively long delays in planning and permitting procedures. Regarding the socio-economic environment, the natural landscape may be moderately negatively affected due to the reduction of visual attractiveness during the installation of the wind farms. The wind farms will have a positive effect on the socio-economic environment. Employment during construction and installation works will be limited and temporary, thus not representing a permanent change for the local population. Income. Construction plots with an area of 8.0079 hectares are allocated for long-term lease for 49 years. As a result, the local budget will receive income from rent, as well as land tax.

The method of paired equations consists of determining the advantages of the elements located in the left column over the elements located in the top row. In this case, a matrix is compiled, the rows and columns of which contain the objects being compared (Table 6). To calculate the priority vector in practice, one of four methods can be used. For this case, we will apply the method of averaging over normalized columns. Based on this method, using the matrix of pairwise comparisons, a normalized matrix is derived, in which the calculation of the priority vectors ω is given (Table 7).

The obtained coefficients of the relative importance of the impact of wind farms on certain environmental components have the following values:

- flora and fauna – 0.337 (33.7%);
- geological environment of the territory and soils – 0.222 (22.2%);
- general health of the population – 0.222 (22.2%);
- air quality – 0.100 (10.0%);
- quality of surface and groundwater – 0.067 (6.7%);
- socio-economic situation of the region – 0.047 (4.7%).

Table 6: Pairwise comparison matrix

Impact of wind farms on environmental components	*Flora and fauna*	*Geological environment of the territory and soils*	*Public health*	*Air quality*	*Groundwater and surface water quality*	*Socio-economic situation*
Flora and fauna	1	5	3	3	4	3
Geological environment of the territory and soils	0.20	1	4	3	6	3
Public health	0.33	0.25	1	6	7	6
Air quality	0.33	0.33	0.17	1	3	4
Groundwater and surface water quality	0.25	0.17	0.14	0.33	1	4
Socio-economic situation	0.33	0.33	0.17	0.25	0.25	1

Table 7: Normalized matrix and calculation of priority vectors

Impact of wind farms on environmental components	*Flora and fauna*	*Geological environment of the territory and soils*	*Public health*	*Air quality*	*Groundwater and surface water quality*	*Socio-economic situation*	$\sum$	$\omega = \sum/6$
Flora and fauna	0.41	0.71	0.35	0.22	0.19	0.14	2.02	0.337
Geological environment of the territory and soils	0.08	0.14	0.47	0.22	0.28	0.14	1.33	0.222
Public health	0.13	0.03	0.12	0.44	0.33	0.28	1.33	0.222
Air quality	0.13	0.05	0.02	0.08	0.14	0.19	0.60	0.100
Groundwater and surface water quality	0.10	0.02	0.02	0.02	0.05	0.19	0.40	0.067
Socio-economic situation	0.14	0.05	0.02	0.02	0.01	0.06	0.28	0.047

Based on the results obtained, it can be concluded that wind farms have the greatest effect on the flora and fauna of the surrounding environment. The impact of wind farms on the general health and geological environment and soils is the same and is 22.2% of the total impact. The least impact of wind farms on the air and surface, and groundwater.

Conclusions

In the present study, an expert-based method is proposed for evaluating the significance of wind farms' impacts on the environment. For this purpose, an algorithm for solving the problem has been developed, which is based on the methods of rank analysis of expert judgments regarding the choice of experts and the impact of wind farms on individual components of the environment has been determined using the method of hierarchy analysis. To implement this algorithm, the most important components of the environment affected by wind farms are identified and the coefficients of their relative importance are calculated, which determine the degree of their effect on the territory. As

a result of the practical implementation of the expert assessment, categories of significance of impacts have been determined, which allow us to conclude that this wind farm has a minor effect on the natural environment. A minor negative impact is the effect on air quality and the socio-economic situation of the region. A moderate negative impact is the effect on the health of the population, on the geological environment of the territory and soils. There is also a moderate negative effect on avifauna due to the relative proximity of the location to forest and wetlands. The most significant impact is on avifauna due to the relative proximity of the location to forests and wetlands. The article does not include studies of the risk of wind farms' impact on cultural heritage, recreation and landscape. Future research should focus on the impacts on the landscape. The results obtained using this methodology of environmental impact assessment will allow determining the significance of potential negative impacts on the environment, as well as positive and negative impacts on the landscape, which will allow judging the actual or potential impact on the environment as a whole.

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Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	*Author 1*	*Author 2*	*Author 3*	*Author 4*	*Author 5*	*Author 6*	*Author 7*
Conceived and designed the research or analysis	Yes	No	Yes	Yes	No	Yes	No
Collected the data	Yes	No	Yes	No	Yes	No	Yes
Contributed to data analysis & interpretation	Yes	Yes	No	Yes	No	No	Yes
Wrote the article/paper	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Critical revision of the article/paper	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Editing of the article/paper	Yes	Yes	Yes	Yes	Yes	Yes	Yes
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The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

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